



**U.S. Army Corps
of Engineers**
Seattle District

Chief Joseph Dam 2012 Two Bay Uplift Spill Test: Total Dissolved Gas Exchange

Prepared by

Kent B. Easthouse
U.S. Army Corps of Engineers, Seattle District
Hydraulics and Hydrology Branch
Water Management Section

Seattle, Washington
September, 2012

Contents

Introduction.....	1
Purpose and Objectives.....	2
Methods and Materials.....	3
Background.....	3
Site Characterization	3
Spillway Tests	3
Existing Fixed Monitoring Stations	4
Study Approach	5
Quality-Assurance Procedures.....	6
Results and Discussion	7
Project Operations	7
Water Temperature	8
TDG Saturations	8
Ambient TDG Conditions	8
Nearfield TDG Conditions	8
Downstream Columbia River.....	10
Conclusions.....	12
References.....	13
Tables.....	14
Figures.....	20

Tables

Table 1. Summary of total dissolved gas and temperature sampling stations.	15
Table 2. Difference between the primary standard thermometer and the laboratory calibrated instrument.	16
Table 3. Summary of project operations from March 26 through March 30, 2012.....	17
Table 4. Statistical summary of total dissolved gas pressures in the Columbia River from March 26 to March 30, 2012.....	18
Table 5. Statistical summary of total dissolved gas saturations in the Columbia River from March 26 to March 30, 2012.	19

Figures

Figure 1. Location of the study area within the Columbia River watershed.	21
Figure 2. TDG and temperature monitoring stations downstream of Chief Joseph Dam to Wells Dam.....	22
Figure 3. TDG and temperature monitoring stations upstream and downstream of Chief Joseph Dam.	23
Figure 4. TDG and temperature monitoring stations at Transect 1 below Chief Joseph Dam.	24
Figure 5. TDG and temperature monitoring stations at Transect 2 below Chief Joseph Dam.	25
Figure 6. TDG and temperature monitoring stations at Transect 3 below Chief Joseph Dam.	26
Figure 7. Right bank spill trajectory (top photo) vs. left bank spill trajectory (bottom photo) during 30 kcfs/bay spillway release.....	27
Figure 8. Chief Joseph Dam tailwater elevations during spillway operations.....	28
Figure 9. Chief Joseph Dam forebay temperature profiles in March and April 2012.	29
Figure 10. Time history of Columbia River temperatures at Transect 1.	30
Figure 11. Time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1.	31
Figure 12. Time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1 showing left bank vs. right bank spill trajectory.....	32

Figure 13. Expanded scale of time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1 showing left bank vs. right bank spill trajectory.	33
Figure 14. Unit spillway discharge vs. TDG saturations for two bay spill events in 2007, 2008, and 2012.	34
Figure 15. Time history of Columbia River TDG saturations as measured downstream of Chief Joseph Dam from Transect T2 to Wells Dam.	35

Introduction

The Seattle District (NWS) conducted a spill test in March 2012 to evaluate the effectiveness of spillway deflectors and joint seal system repairs at reducing uplift pressure increases measured during spillway operations at Chief Joseph Dam in the 1990's. During high spill rates, increases in uplift pressures were measured in some of the uplift pressure cells located under the spillway of Chief Joseph Dam. Uplift pressures for spill over deflectors with a repaired seal system were measured during previous spill tests conducted in 2007 and 2008. These spill tests discharged up to 16 thousand cubic feet per second (kcfs) per bay over two spillway bays (bays 12 and 13) that contain instrumentation for measuring uplift pressures. These tests showed improved uplift pressures over pre-deflector/seal repair conditions in the 1990's, but there were still instruments showing rising uplift pressures at the end of the 16 kcfs per bay test in 2007 and 2008.

Installation of all joint seal upgrades for the Chief Joseph spillway was completed in 2009. High spring runoff conditions in both 2010 and 2011 resulted in increased long duration spill events over all 19 spillway bays at Chief Joseph Dam in those years. Although uplift pressures remained very low during these spill events, the maximum spill rates were only about 10 kcfs/bay (less than 20% of the spillway potential 63 kcfs/bay). The two previous spill tests in 2007 and 2008 measuring uplift pressures at 16 kcfs/bay were inconclusive and uplift pressures for spillway discharges greater than 16 kcfs per bay up to the maximum of 63 kcfs per bay have not been tested. Because the addition of spillway deflectors has changed the frequency and manner in which the spillway will be used there is a possibility of spilling greater amounts per bay for longer durations in the future. Consequently, the Seattle District conducted a spill test which evaluated the combined effect of the monolith joint seal improvements and changes in pressure distribution due to the installation of the deflectors on uplift pressures for spill rates of 30 kcfs/bay and 40 kcfs/bay.

Total dissolved gas (TDG) supersaturation is generated in the Columbia River during spillway flows at Chief Joseph Dam. The absorption of atmospheric gasses is caused by the entrainment of air bubbles into a plunging spill jet resulting in the transfer of gas into solution at depth in the stilling basin. A detailed investigation of pre-deflector TDG exchange was conducted at Chief Joseph Dam in 1999 and an investigation of post-deflector TDG exchange was conducted in 2009 (Schneider and Carroll 1999; Schneider 2012). The pre-deflector study determined that TDG exchange in spillway flows ranged from about 111 to 134 percent and were a direct function of the specific spillway discharge. The post-deflector study showed that spillway deflectors substantially reduced TDG exchange in spillway flows with measured TDG saturations ranging from about 110 to 120 percent. An investigation of TDG exchange for spill over two bays with deflectors was conducted in 2007 (Schneider 2008). This study determined that TDG exchange in spillway flows of 16 kcfs/bay over two bays ranged up to 122 percent saturation.

Total dissolved gas (TDG), water temperature, and associated water quality processes are known to impact anadromous and resident fishes in the Columbia River. Dams may alter a river's water quality characteristics by increasing TDG levels due to releasing water through the spillways and by altering temperature gradients due to the creation of reservoirs. Spilling water at dams can

result in increased TDG levels in downstream waters by plunging the aerated spill water to depth where hydrostatic pressure increases the solubility of atmospheric gases. Elevated TDG levels generated by spillway releases from dams can promote the potential for gas bubble trauma in downstream aquatic biota (Weitkamp and Katz 1980; Weitkamp et al. 2002); this condition is analogous to decompression sickness, or “the bends,” in human divers. Water temperature has a significant impact on fish survivability, TDG saturations, the biotic community, chemical and biological reaction rates, and other aquatic processes.

To address uplift pressure concerns during spillway operations, the Corps conducted a two bay spill test during March 2012. Two distinct spillway releases of 30 kcfs/bay and 40 kcfs/bay were scheduled during the study.

Purpose and Objectives

The purpose of the TDG study is to quantify total dissolved gas exchange processes associated with two bay spillway operations at Chief Joseph Dam and the resultant transport and mixing in the Columbia River below the project for a distance of about 30 miles to Wells Dam. Although two bay spillway operations are not common, this type of spill is periodically used to assess dam safety and uplift pressure concerns at Chief Joseph Dam. Consequently, quantifying TDG exchange during two bay spill discharges provides the Seattle District with valuable information for better assessing the potential water quality and biological impacts to the Columbia River from this type of spill test. The major objectives of this study were:

- To monitor TDG saturations in the Columbia River during two bay spillway releases
- To study the lateral mixing of spill and powerhouse water in the Columbia River downstream of Chief Joseph Dam during two bay spillway releases
- To study TDG exchange properties in the Columbia River downstream of Chief Joseph Dam.

These objectives were addressed using data collection and analysis methods to evaluate temperature and TDG exchange characteristics in the Columbia River before, during, and after spillway operations. The study focused on the Columbia River from Chief Joseph Dam to Wells Dam, Washington.

Methods and Materials

Background

Site Characterization

The Columbia River originates in the Rocky Mountains of British Columbia at an elevation exceeding 3,000 meters and flows northward for several hundred kilometers before flowing southward through a series of lakes and reservoirs toward the state of Washington (Figure 1). The Kootenai River and the Pend Oreille River enter the Columbia River north of the international border, and the Columbia River flows into Lake Roosevelt immediately south of the border. Lake Roosevelt is the 210 kilometer long reservoir formed by Grand Coulee Dam, a Bureau of Reclamation (BOR) project located at river kilometer 960. Downstream of Grand Coulee Dam the river enters Rufus Woods Lake, the 80 kilometer long reservoir formed by Chief Joseph Dam, a COE project. Chief Joseph Dam is a concrete gravity dam, 70.1 meters high, with 19 spillway bays which abut the right bank. The spillway is controlled by 11-meter wide by 17.7-meter high tainter gates and is designed to pass releases up to 1,200 kcfs at a maximum water surface elevation of 292.2 meters.

The study area lies within the high-steppe, semiarid desert region of central Washington (Figure 2). The Columbia River in the study area forms the boundary between two distinct geologic provinces in the State of Washington, the Okanogan Highlands to the north and the Columbia Plateau to the south (WDNR 2004). The Okanogan Highlands are characterized by rounded mountains and narrow valleys, and are dominated by metasedimentary rocks. The Columbia Plateau is characterized by incised rivers, extensive plateaus, and anticlinal ridges. The Plateau region is dominated by basalt flows laid down by successive volcanic eruptions during the Miocene (WDNR 2004). Elevations range from about 236 meters at the Columbia River immediately downstream of Chief Joseph Dam to over 1,000 meters in the mountainous terrain that rise up from the water in the mid to upper reaches of the reservoir.

The climate of the study area is influenced by easterly moving weather systems from the Pacific Ocean. Winters are generally cool with November through March being the wettest months. Summers are warm and dry with little to no precipitation falling from June through September. The mean annual precipitation in the vicinity of the dam is about 25 centimeters. Total annual snowfall varies with elevation throughout the study area, with about 40 centimeters near the dam. The mean annual temperature at the dam is 10°C, with extremes recorded in the vicinity of the dam of – 30°C and 43°C (USCOE 1985).

Spillway Tests

A detailed investigation of TDG exchange at Chief Joseph Dam with the original spillway was conducted in 1999 (Schneider and Carroll, 1999). This investigation determined the TDG

exchange in spillway flows ranged from 111 to 134 percent and were a direct function of the specific spillway discharge. The maximum TDG saturation observed in the aerated spillway release during this study was 174 percent of saturation. The maximum TDG threshold produced during spillway flows was also found to be a function of the tailwater depth of flow. This process was responsible for spillway flow to generate significantly higher TDG saturation than observed during the spill test in 1999.

The construction of two spillway flow deflectors on Bays 12 and 13 were completed by April of 2007 and the TDG exchange properties were evaluated during scheduled spillway operations on April 22-23, 2007 for spill ranging from 3.9 to 31.2 kcfs (about 2 to 16 kcfs per bay). A linear relationship between spill discharge and TDG saturation was observed during the two bay spill tests with the resultant maximum TDG saturation outside of aerated flow of about 120 to 122 percent for the 16 kcfs per bay event. The size of the entrainment discharge associated with the two bay spill pattern moderated the observed TDG saturation (Schneider, 2008).

Spillway deflector construction was completed in 2009. A spillway deflector TDG exchange study was conducted at Chief Joseph Dam from April 28 to May 1, 2009 to determine the TDG exchange characteristics for Chief Joseph Dam with deflectors. Spillway discharges ranged from 18 to 145 kcfs (about 1 to 7 kcfs per bay) during this study. Results showed the TDG exchange during spillway operations with deflectors was greatly reduced compared to non-deflector operations (Schneider 2012). For spillway flows over 38 kcfs the magnitude of reduction in TDG saturation approached 15 percent saturation with spillway flow deflectors. Prior to the addition of spillway flow deflectors at Chief Joseph Dam, a spillway discharge of as little as 36 kcfs resulted in TDG saturations greater than 120 percent saturation. With spillway flow deflectors, a uniform spill of 142 kcfs was sustained with TDG levels remaining slightly below 120 percent saturation. TDG saturations were lowest for uniform spillway conditions with TDG exchange to be influenced by tailwater depth, with higher tailwater depth resulting in greater TDG saturations.

Existing Fixed Monitoring Stations

Based on the lateral transect TDG saturation data collected by Schneider and Carroll (1999), the Seattle District installed a fixed monitoring TDG station (CHQW) on the right bank about 1.3 miles downstream of the spillway (Figure 2). Schneider and Carroll (1999) measured TDG saturations along a lateral transect in the Columbia River immediately downstream of the aerated zone and measured the highest TDG saturations along the right bank. Although monitoring in the aerated zone (i.e. immediately downstream of the stilling basin) recorded higher TDG saturations, it is generally not recommended for monitoring stations because the highly turbulent aerated water results in dynamic TDG saturations. A rapid and substantial desorption of supersaturated gas takes place in the aerated zone immediately downstream of the stilling basin resulting in difficulty accurately measuring TDG saturations. An existing forebay fixed monitoring station (CHJ) is located on the left bank at the boathouse immediately upstream of the powerhouse (Figure 2).

Study Approach

An array of thirteen (13) instruments, consisting of eleven (11) data loggers and two (2) real-time instruments, were deployed in the Columbia River to measure lateral and longitudinal TDG saturations and temperature in the Columbia River generated by Chief Joseph Dam powerhouse and spillway operations. The general locations of these water quality monitoring stations are shown in Figures 2, 3, 4, 5, and 6, and a description of each station is presented in Table 1. Data were collected by the water quality instrumentation at either 15 minute intervals (data loggers) or 60 minute intervals (real-time probes) and included the date, time, instrument depth, water temperature, TDG pressure, and internal battery voltage. In addition, barometric pressure and air temperature were monitored near Chief Joseph Dam at the forebay and tailwater fixed monitoring stations to calculate the TDG percent saturation.

Two real-time instruments were deployed in the Columbia River at the forebay (CHJ) and tailwater (CHWQ) of Chief Joseph Dam (Figures 2 and 3). Station CHJ is the permanent forebay fixed monitoring station for Chief Joseph Dam and is positioned in the forebay near the left bank immediately upstream of the powerhouse. The probe was deployed directly into the water off of the boathouse's floating dock at a depth of about 20 feet. This upstream station is representative of TDG saturations resulting from powerhouse discharges. Station CHWQ is the permanent tailwater fixed monitoring station for Chief Joseph Dam and is positioned along the right bank of the river, 1.3 miles downstream from the spillway at a location representing about 5 percent normalized distance from the right bank (i.e. 95% from the left bank). The TDG probe was deployed in an anchored perforated PVC pipe that extended out into the river below the TDG compensation depth but not to the bottom of the river.

Eleven data loggers were deployed in the Columbia River for the study. Six data loggers (T1P1, T1P2, T1P3, T1P4, T1P5, and T1P6) were deployed in the river about 1.3 miles downstream of the spillway at the location of the tailwater Fixed Monitoring Station as outlined in Table 1 and shown in Figure 4. These instruments were deployed along a transect with station CHWQ to monitor the lateral mixing between spillway and powerhouse flows. The sampling stations were skewed towards the right bank to best capture the development of the mixing zone between spillway and powerhouse flows. These stations were positioned in a transect representing 10, 30, 50, 70, 90, and 95 percent normalized distance from the left bank (Figure 4 and Table 1).

The remaining sampling stations were located about 7, 14, and 29 miles downstream of the project to measure the TDG pressures in the Columbia River under open-channel flow conditions and before encountering Brewster Flats and the Okanogan River (Figures 5 and 6). Three instruments (T2P1, T2P2, and T2P3) were located about 7 miles downstream in the Columbia River positioned in a transect representing 10, 50, and 90 percent normalized distance from the left bank. Instrumentation for these stations were housed in a perforated PVC pipe housing and deployed near the bottom of the river with weights and cables. One instrument (T3P1) was located about 14 miles downstream in the Columbia River at the highway bridge crossing in Brewster Washington, and positioned at 50 percent normalized distance from the left bank. The farthest downstream sampling station consisted of one instrument (WELLFB) located about 29 miles downstream of Chief Joseph Dam in the forebay of Wells Dam, as shown previously in

Figure 2. This instrument was located about 20 feet deep at the end of a cable and was free to move with the transient current at this location

All water quality probes used in the study were Hydrolab MiniSonde MS4A/MS5 TDG probes. Additional instrumentation for both real-time stations consisted of a Common Sensing TBO-L electronic barometer, a Sutron 9210 X Lite DCP, a radio transmitter, and a power source. For real-time stations, the barometer, TDG probe and DCP were powered by a 12-volt battery that was charged by a 120-volt AC line.

Quality-Assurance Procedures

Data quality assurance and calibration procedures included calibration of instruments in the laboratory following procedures outlined in the *Corps of Engineers Plan of Action for Dissolved Gas Monitoring 2011* (USACE 2010). All primary standards were National Institute of Science and Technology (NIST) traceable and maintained according to manufacturers' recommendations. A new TDG membrane was assigned to each probe at the beginning of the study.

Water quality probes were laboratory calibrated using the following procedures. TDG pressure sensors were checked in air with the membrane removed. Ambient pressures determined from the NIST traceable mercury barometer served as the zero value for total pressure. The slope for total pressure was determined by adding known pressures to the sensor. Using a NIST traceable digital pressure gauge, comparisons were made at pressures of 0 and 300 mm mercury (Hg) above barometric pressure, which represented TDG saturations from 100 to 139% (Table 2). If any measurement differed by more than 5 mm Hg from the primary standard, the sensor was adjusted and rechecked over the full calibration range. As seen in Table 2, most calibrations were within 0 to 2 mm Hg of total dissolved gas.

Laboratory calibrations of the water quality probe's temperature sensor were performed using a NIST traceable thermometer and are shown in Table 2. If the measurements differed by more than 0.2°C, the probe was not used. As seen in Table 2, most calibrations were within 0.1°C for temperature.

Once the real-time data and logger data were received and missing data were flagged, the following quality assurance review procedures occurred. First, tables of raw data were visually inspected for erroneous data resulting from DCP malfunctions or improper transmission of data value codes. Second, data tables were reviewed for sudden increases in temperature, barometric pressure, or TDG pressure that could not be correlated to any hydrologic event and therefore may be a result of mechanical problems. Third, graphs of the data were created and analyzed in order to identify unusual spikes in the data. A quality assurance review of all stations showed that Station T1P1 failed to log data for the entire deployment period and consequently no data from that station was used. All other data were acceptable and were used in this report.

Results and Discussion

Project Operations

Water quality instruments were deployed on March 26th and removed on March 30th, 2012. During this time period, total river discharge from Chief Joseph Dam ranged from about 110 kcfs to 180 kcfs, while spillway releases ranged from 0 kcfs to 80 kcfs. A total of 5 distinct events were classified during this time period (Table 3). From 1600 March 26 to 0700 March 27 no spill was scheduled, and this period of non-spill background conditions represents Event 1. From 0700 March 27 to 2300 March 28 spill of 30 kcfs/bay from two bays (spillway bays 12 and 13) were scheduled, and this spill volume represents Events 2 and 3. Event 2 occurred from 0700 March 27 to 2300 March 27 when spillway releases maintained a right bank spill trajectory (Figure 7). Event 3 occurred from 2300 March 27 to 2300 March 28 when spillway releases moved from the right bank to the left bank and maintained a left bank spill trajectory (Figure 7). From 2300 March 28 to 0600 March 29 spill of 40 kcfs/bay from two bays (spillway bays 12 and 13) were scheduled representing Event 4. The spill test concluded at 0600 on March 29th. For data management purposes, the 27 hours of spill following the conclusion of the two bay test was classified as Event 5. This spill event occurred from 0600 March 29 to 0900 March 30 and consisted of spill of 1kcfs from 18 spillway bays.

Spillway releases from bays 12 and 13 were conducted from 0700 March 27th through 0600 March 29th, 2012, with spill discharge ranging from 30 kcfs/bay to 40 kcfs/bay (Table 3). The powerhouse generation flow rate during the test was constantly changing as scheduled power production was updated and flow adjustments were implemented. In general, powerhouse flows were in the 80 kcfs to 110 kcfs range during the two bay spill test (Table 3). Tailwater elevations ranged from a low of about 781.7 feet at the start of spill during Event 2 to a high of 786.7 feet during Event 3 (Figure 8). The goal of the powerhouse flows was to (1) provide sufficient depth of submergence over the deflectors to prevent plunging flow conditions and (2) provide sufficient flow of low TDG water to mix with high TDG spill water to reduce the mixed river TDG saturations and minimize any downstream impacts. After the start of spill during Event 2, the tailwater elevation quickly increased and ranged only about 3 feet during spillway discharges, resulting in relatively constant depths for the water quality probes located downstream. The depths of all probes ranged from about 20 to 30 feet along Transect 1, 30 to 50 feet along Transect 2, and 15 feet at Transect 3. The depths of the probes placed at the forbay of Wells and Chief Joseph were greater than 20 feet. Consequently, all water quality probes were deeper than the compensation depth of 10 feet required to accurately measure a TDG saturation of 135%. The compensation depth is the depth above which degassing will occur due to decreased hydrostatic pressure. To measure TDG accurately, a probe must be placed below the minimum calculated compensation depth.

Water Temperature

The forebay of Chief Joseph Dam was not thermally stratified during the study period. Forebay temperature profiles from March 13th and April 11th at 1500 hours are shown in Figure 9. Water temperatures from the surface to over 60 meters deep in the forebay showed little change and ranged from about 2.8°C in March to about 4.8°C in April. Consequently, little difference in water temperature would be expected between spillway flows and powerhouse flows. Figure 10 shows that no lateral water temperature gradients were measured in the Columbia River at Transect 1 due to the combined spillway and powerhouse releases. The slight 0.1 to 0.2 °C difference noted along the transect represent differences in temperature calibrations as these differences exist during flow through the powerhouse in Event 1 prior to any spillway release.

TDG Saturations

Total dissolved gas levels presented in the following sections are reported as either TDG pressure in millimeters (mm) Hg or as TDG saturation (percent). Water quality monitoring stations providing information on nearfield TDG processes were stations T1P2-6 and CHQW while ambient conditions were measured at forebay station CHJ (see Figure 4). Information on downstream TDG processes were stations T2P1-3, T3P1, and WELLFB (see Figures 2, 5 and 6). A statistical summary of the TDG pressures and saturations at all water quality stations for event spillway conditions are presented in Tables 4 and 5.

Ambient TDG Conditions

The ambient TDG pressures measured upstream of Chief Joseph Dam (station CHJ) were relatively constant throughout the study and did not vary by more than ± 4 mmHg, with saturations remaining near 102 percent for Events 1 through 5. Pre-spill TDG saturations measured during Event 1 generally ranged from about 101 to 103 percent across the sampling array as shown in Table 5. The TDG saturations prior to spill were similar upstream of Chief Joseph Dam (station CHJ) and across all downstream stations indicating that station CHJ is representative of TDG saturations passing through the powerhouse.

Nearfield TDG Conditions

During two-bay spillway releases from bays 12 and 13, TDG saturations measured along Transect 1 showed the development of lateral gradients in TDG between spillway flows along the right bank (stations T1P4-6 and CHQW) and powerhouse flows along the left bank (stations T1P2-3) (Figure 11). The development of a mixing zone results in the redistribution of TDG pressures at Transect T1, with highest TDG saturations measured near the right bank and lower TDG saturations measured near the left bank. Because station T1P1 (located at the 10% normalized distance from the left bank) failed to operate, TDG saturations on the far left bank associated with unaltered powerhouse discharge were not measured. As seen in Figure 11, TDG saturations measured at station T1P2 (located at the 30% normalized distance from the left bank)

show some influence of spillway TDG mixing with powerhouse flows. TDG saturations measured at T1P3 (50% normalized distance from left bank) and T1P4 (70% normalized distance from left bank) show increasing influences from spillway TDG pressures. Stations T1P5 (90% normalized distance from left bank), T1P6 (95% normalized distance from left bank) and CHQW (95% normalized distance from left bank) were similar during the study and generally representative of spillway TDG pressures with little mixing of powerhouse flows.

The TDG saturations measured at Transect 1 during Events 2 and 3 are shown in Figure 11. For Event 2, median TDG saturations along Transect 1 ranged from 107.5% (792 mm Hg) near the left bank at T1P2 to 125.4% (923 mm Hg) near the right bank at T1P5 (Tables 4 and 5). The maximum TDG saturations of 126.1% (927 mm Hg) were measured at the 90% normalized distance from the left bank with slightly lower TDG saturations measured at the 95% distance. For Event 3, median TDG saturations along Transect 1 ranged from 105% (770 mm Hg) near the left bank at T1P2 to 128.4% (941 mm Hg) on the right bank at CHQW (Tables 4 and 5). Maximum TDG saturations of 129.5 % (951 mm Hg) during Event 3 were similar between right bank stations at the 90% (T1P5) and 95% (T1P6 and CHQW) normalized distance.

Events 2 and 3 represent a spillway discharge of 30 kcfs/bay from bays 12 and 13 with similar powerhouse discharges of about 100 kcfs (Table 3). However, these two events are differentiated by a change in the spillway trajectory from the right bank (Event 2) to the left bank (Event 3) as shown in Figure 7. The change in spill trajectory from the right bank (Event 2) to the left bank (Event 3) resulted in about a 3% (20 mm Hg) increase in TDG levels measured at stations located near the right bank in predominately spillway flow (T1P5, T1P6, CHQW) (Figures 12 and 13). However, a decrease in TDG levels of about 2-3% (10-20 mm Hg) was measured at stations located either near the left bank in more powerhouse flow (T1P2 and T1P3) or at the 70% distance in the mixing zone (T1P4). It is uncertain why the spill trajectory moved from the right bank to the left bank during the 30 kcfs/bay spillway release from bays 12 and 13. It is possible that a shift in powerhouse units being operated from the southern end of the powerhouse to the northern end of the powerhouse resulted in the formation of an eddy that transitioned the spill trajectory from the right bank to the left bank. The maximum TDG saturations measured along Transect 1 during the 30 kcfs/bay spill were the result of the spill having a left bank trajectory as seen in Event 3.

The TDG saturations measured at Transect 1 during Event 4 is shown in Figure 11. Event 4 represents an increase in spillway discharge from 30 kcfs/bay to 40 kcfs/bay, a slight decrease in powerhouse discharge from about 100 kcfs to 80 kcfs, and continued left bank spillway trajectory (Table 3). For Event 4, median TDG saturations along Transect 1 ranged from 109.2% (802 mm Hg) near the left bank at T1P2 to 132.1% (970 mm Hg) on the right bank at CHQW (Tables 4 and 5). Maximum TDG saturations of 133.2 % (978 mm Hg) were measured at T1P5 with similar maximum TDG levels (132.7% to 132.8%) measured at stations T1P6 and CHQW, respectively.

Event 5 represents normal spillway operations after the end of the two-bay spill test (Figure 11). During Event 5, spillway discharge was via a uniform pattern of 1 kcfs/bay from 18 bays with a powerhouse discharge of about 128 kcfs. Median TDG saturations along Transect 1 ranged from

102.2% (743 mm Hg) near the left bank at T1P2 to 108.0% (785 mm Hg) on the right bank at CHQW (Tables 4 and 5).

The median TDG saturations for two-bay spillway discharges of 30 kcfs/bay and 40kcfs/bay from bays 12 and 13 clearly show the development of strong lateral gradients in TDG saturations, with TDG extending farther across the river for the 40kcfs/bay spill event. During the two-bay tests, the maximum TDG was observed along the right bank at the 90% normalized distance from shore with slightly lower TDG levels measured along the right bank at the 95% normalized distance. For spillway flows of 30 kcfs/bay, elevated TDG saturations extended across at least 50 percent of the Columbia River. For spillway flows of 40 kcfs/bay, elevated TDG saturations extended across at least 70 percent of the Columbia River.

The TDG saturation data collected at station CHQW during the two-bay test indicates that the unit spillway discharge is an important causal parameter in determining the TDG exchange in spillway flows at Chief Joseph Dam. Figure 14 shows station CHQW TDG saturations as a function of unit spillway discharge. Data collected during two-bay spill events in 2007 and 2008 are included in the figure. A linear relationship between TDG saturation at station CHQW and unit spillway discharge was apparent over the range of 2 to 40 kcfs/bay. The polynomial equation of the line is as follows:

- $TDG_{sp} = -0.0048q^2 + 0.836q + 105.99 \quad (r^2 = 0.9562)$

Where:

- TDG_{sp} = Total Dissolved Gas Saturation in Spillway Discharges (%)
- q = Unit Spillway Discharge (kcfs/bay)

Increases in TDG saturations between Event 2 and 3 when unit spillway discharge was held constant at 30 kcfs/bay suggest that spillway trajectory is another important parameter in determining TDG exchange in spillway flows at Chief Joseph Dam. Even though the unit spillway discharge remained stable at 30 kcfs/bay, maximum TDG saturations measured along Transect 1 increased by about 3% (20 mm Hg) when the spill trajectory shifted from the right bank to the left bank.

Downstream Columbia River

Downstream TDG processes were monitored in the Columbia River at distances of about 7 miles (Transect 2), 14 miles (Transect 3), and 29 miles (Wells Dam Forebay) downstream of Chief Joseph Dam (see Figure 2). Schneider (2012) concluded that during spillway operations, Columbia River TDG saturations were generally well mixed at about 14 miles downstream of the dam at the Brewster WA Highway Bridge, and continued to be well mixed downstream to Wells Dam. In-river processes such as lateral mixing, tributary dilution, degassing at the air-water interface, thermal heat exchange, and biological productivity are likely responsible for TDG saturations in the Columbia River becoming mixed downstream (Schneider 2012).

TDG saturations measured downstream of Transect 1 (see Figure 2) decreased with distance from Chief Joseph Dam as the river approached Wells Dam (Figure 15). Lateral TDG gradients were present at Transect 2 showing the continued development of the mixing zone between powerhouse flows along the left bank and spillway flows on the right bank. The TDG saturations measured at Transects 2 and 3 are shown in Figure 15. For Event 2, median TDG saturations along Transect 2 ranged from 114.8% (846 mm Hg) near the left bank at T2P1, 117.1% (863 mm Hg) at the mid-river station T2P2, to 118.7% (874 mm Hg) near the right bank at T2P3 (Tables 4 and 5). For Event 3, median TDG saturations along Transect 2 ranged from 113.5% (833 mm Hg) near the left bank at T2P1, 115.9% (849 mm Hg) at the mid-river station T2P2, to 118.0% (865 mm Hg) near the right bank at T2P3 (Tables 4 and 5). Maximum TDG saturations along Transect 2 for Events 2 and 3 were consistently measured at the 90% normalized distance from the left bank. Median TDG saturations measured at Transect 3 ranged from 116.8% (858 mm Hg) for Event 2 to 115.7% (847 mm Hg) for Event 3. Schneider (2012) calculated the average travel time from Chief Joseph Dam to Transects 2 and 3 during spillway discharge tests in 2009 to range from 3.5 to 4.5 hours to Transect 2 and from 7 to 9 hours to Transect 3, depending on flow and the elevation of Wells Pool. This range of travel times was used to calculate the median, maximum, and minimum TDG values for each event at Transects 2 and 3 (Table 4 and 5).

The TDG saturations measured at Transects 2 and 3 during Event 4 are shown in Figure 15. For Event 4, median TDG saturations along Transect 2 ranged from 117.8% (864 mm Hg) near the left bank at T2P1, 118.5% (870 mm Hg) at the mid-river station T2P2, to 122.1% (895 mm Hg) near the right bank at T2P3 (Tables 4 and 5). Maximum TDG saturations along Transect 2 for Event 4 were consistently measured at the 90% normalized distance from the left bank. Event 5 represents normal spillway operations after the end of the two-bay spill test. Median TDG saturations along Transect 2 ranged from 103.0% (749 mm Hg) near the left bank at T2P1 to 104.2% (758 mm Hg) near the right bank at T2P3 (Tables 4 and 5). Median TDG saturations measured at Transect 3 ranged from 119.0% (872 mm Hg) for Event 4 to 103.4% (751 mm Hg) for Event 5.

The passage of the spill events at the Wells Dam forebay station (WELLFB) was not as prominent as for stations located at Transects 2 and 3 (Figure 15). Downstream TDG saturations measured at Wells Dam Forebay (Station WELLFB) show the influence of in-river processes such as lateral mixing, tributary dilution and degassing at the air-water interface. Schneider (2012) calculated the average travel time from Chief Joseph Dam to Wells Dam during spillway discharge tests in 2009 to range from 20 to 24 hours depending on flow and the elevation of Wells Pool. This range of travel times was used to calculate the median, maximum, and minimum TDG values for each event at the Wells Dam forebay station (Table 4 and 5). Median TDG saturations measured at station WELLFB ranged from 114.7% (842 mm Hg) for Event 2 to 115.0% (841 mm Hg) for Event 3, and from 116.9% (850 mm Hg) for Event 4 to 103.8% (759 mm Hg) for Event 5.

Conclusions

- During two-bay spillway releases from bays 12 and 13, TDG saturations measured along Transect 1 showed the development of lateral gradients in TDG between spillway flows along the right bank and powerhouse flows along the left bank. The development of a mixing zone results in the redistribution of TDG pressures at Transect T1, with highest TDG saturations measured near the right bank and lower TDG saturations measured near the left bank.
- The median TDG saturations for two-bay spillway discharges of 30 kcfs/bay and 40kcfs/bay from bays 12 and 13 clearly show the development of strong lateral gradients in TDG saturations, with TDG extending farther across the river for the 40kcfs/bay spill event. During the two-bay tests, the maximum TDG was observed near the right bank at the 90% normalized distance from shore with slightly lower TDG levels measured along the right bank at the 95% normalized distance.
- The TDG saturation data collected at station CHQW during the two-bay test indicates that the unit spillway discharge is an important causal parameter in determining the TDG exchange in spillway flows at Chief Joseph Dam. Similar results were measured in 2007 and 2008 during two-bay spill tests. A linear relationship between TDG saturation at station CHQW and unit spillway discharge was apparent over the range of 2 to 40 kcfs/bay.
- Increases in TDG saturations between Event 2 and 3 when unit spillway discharge was held constant at 30 kcfs/bay suggest that spillway trajectory is an important parameter in determining TDG exchange in spillway flows at Chief Joseph Dam.
- TDG saturations measured downstream decreased with distance from Chief Joseph Dam as the river approached Wells Dam. Lateral TDG gradients were present about 7 miles downstream at Transect 2 showing the continued development of the mixing zone between powerhouse flows along the left bank and spillway flows on the right bank.
- The passage of the spill events at the Wells Dam forebay station (WELLFB) was not as prominent as for stations located at Transects 1, 2 and 3. Downstream TDG saturations measured at Wells Dam show the influence of in-river processes such as lateral mixing, tributary dilution and degassing at the air-water interface.

References

Schneider, M.L. 2008. Chief Joseph Dam: Post deflector field investigation of total dissolved gas exchange during spill over bays 12 and 13. Prepared for the Seattle District Corps of Engineers by the U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Schneider, M.L. 2012. Total dissolved gas exchange at Chief Joseph Dam: Post spillway deflectors April 28-May 1, 2009. Prepared for the Seattle District Corps of Engineers by the U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Schneider, M.L. and Carroll, J.C. 1999. TDG exchange during spillway releases at Chief Joseph Dam, near-field study, June 6-10, 1999. Prepared for the Seattle District Corps of Engineers by the U.S. Army Waterways Experiment Station, Vicksburg, MS.

USCOE 1985. Chief Joseph Dam, Columbia River, Washington Water Control Manual. U.S. Army Corps of Engineers, Seattle District.

USCOE 2010. Corps of Engineers plan of action for dissolved gas monitoring for 2011. North Pacific Division, Water Management Division, Reservoir Control Center, Water Quality Unit, Portland, Oregon.

WDNR 2004. The Geology of Washington. Washington Department of Natural Resources, Web address: <http://www.dnr.wa.gov/geology/geolofwa.htm>, Olympia, WA.

Weitkamp, D.E. 1980. A review of dissolved gas supersaturation literature. Transactions of the American Fisheries Society, 109:659-702.

Weitkamp, D.E., Sullivan, R.D., Swant, T., and J. DosSantos. 2002. Gas bubble disease in resident fish of the Lower Clark Fork River. Report prepared for Avista Corporation by Parametrix, Inc.

Tables

Table 1. Summary of total dissolved gas and temperature sampling stations.

Station Name	Latitude	Longitude	Station Description	Station Location
T1P1	48.003410	-119.661220	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 10% distance from left bank
T1P2	48.003700	-119.660550	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 30% distance from left bank
T1P3	48.004080	-119.660190	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 50% distance from left bank
T1P4	48.004129	-119.659236	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 70% distance from left bank
T1P5	48.004450	-119.658798	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 90% distance from left bank
T1P6	48.004743	-119.658694	2.1 kilometers downstream of spillway, lateral transect	Transect 1: 95% distance from left bank
T2P1	48.069560	-119.672090	11.2 kilometers downstream of spillway, lateral transect	Transect 2: 10% distance from left bank
T2P2	48.069360	-119.670270	11.2 kilometers downstream of spillway, lateral transect	Transect 2: 50% distance from left bank
T2P3	48.068830	-119.668460	11.2 kilometers downstream of spillway, lateral transect	Transect 2: 90% distance from left bank
T3P1	48.086767	-119.781517	22.5 kilometers downstream of spillway, Brewster Wa Highway Bridge	Transect 3: 50% distance from left bank
CHJ	47.993890	-119.645280	Forebay immediately upstream of powerhouse	Forebay: 5% distance from left bank
CHQW	48.004720	-119.658330	2.1 kilometers downstream of spillway, Wells Dam forebay	Transect 1: 95% distance from left bank
WELLFB	48.947688	-119.863309	46.7 kilometers downstream of spillway, lateral transect	Forebay: 50% distance from left bank

Table 2. Difference between the primary standard thermometer and the laboratory calibrated instrument.

Station Name	Date	Calibration Type	Deviation from Temp Standard	Deviation from TDG Standard (mm Hg)	
			Temp, °C	BP + 0	BP + 300
T1P1	03/23/12	Pre-Deployment	0.1	1	1
T1P2	03/23/12	Pre-Deployment	0.1	1	1
T1P3	03/23/12	Pre-Deployment	0.0	1	0
T1P4	03/23/12	Pre-Deployment	-0.1	1	0
T1P5	03/23/12	Pre-Deployment	0.1	1	0
T1P6	03/23/12	Pre-Deployment	0.0	0	0
T2P1	03/23/12	Pre-Deployment	0.0	0	0
T2P2	03/23/12	Pre-Deployment	0.2	1	1
T2P3	03/23/12	Pre-Deployment	-0.2	1	0
T3P1	03/23/12	Pre-Deployment	0.0	1	1
CHJ	03/21/12	Pre-Deployment	-0.1	1	1
CHQW	03/21/12	Pre-Deployment	-0.1	1	1
WELLFB	03/22/12	Pre-Deployment	-0.1	0	0
T1P1	03/30/12	Post-Deployment	—	0	0
T1P2	03/30/12	Post-Deployment	—	1	1
T1P3	03/30/12	Post-Deployment	—	1	1
T1P4	03/30/12	Post-Deployment	—	0	0
T1P5	03/30/12	Post-Deployment	—	2	0
T1P6	03/30/12	Post-Deployment	—	-1	-1
T2P1	03/30/12	Post-Deployment	—	0	0
T2P2	03/30/12	Post-Deployment	—	0	0
T2P3	03/30/12	Post-Deployment	—	1	1
T3P1	03/30/12	Post-Deployment	—	1	1
CHJ	04/06/12	Post-Deployment	0.0	0	0
CHQW	04/06/12	Post-Deployment	0.0	0	0
WELLFB	—	Post-Deployment	—	—	—

Table 3. Summary of project operations from March 26 through March 30, 2012.

Starting Date and Time	Ending Date and Time	Duration (hours)	Mean Spill (kcfs)	Mean Spill Per Bay (kcfs/bay)	Mean River Flow (kcfs)	Mean Powerhouse Flow (kcfs)	Event Number	Notes
26-Mar-2012 16:00	27-Mar-2012 07:00	15	0	0	145	145	1	Background, non-spill conditions
27-Mar-2012 07:00	27-Mar-2012 23:00	16	60	30	163	103	2	Right bank spill trajectory
27-Mar-2012 23:00	28-Mar-2012 23:00	24	60	30	160	100	3	Left bank spill trajectory
28-Mar-2012 23:00	29-Mar-2012 06:00	7	80	40	167	87	4	Left bank spill trajectory
29-Mar-2012 06:00	30-Mar-2012 09:00	27	18	1	146	128	5	Uniform spill 1 kcfs from 18 bays

Table 4. Statistical summary of total dissolved gas pressures in the Columbia River from March 26 to March 30, 2012.

Event	Data	T1P2	T1P3	T1P4	T1P5	T1P6	T2P1	T2P2	T2P3	T3P1	CHJ	CHQW	WELLFB
1	Median	745	744	745	743	741	743	758	746	742	743	744	750
	Maximum	746	745	746	746	747	744	758	747	747	745	753	753
	Minimum	743	743	744	743	741	742	752	746	742	743	743	747
	Count	45	45	45	45	45	41	41	41	51	14	14	75
2	Median	792	854	902	923	916	846	863	874	858	744	916	842
	Maximum	814	872	912	927	921	856	867	881	865	744	918	843
	Minimum	767	823	872	899	911	831	857	863	832	742	908	818
	Count	57	57	57	57	57	55	55	55	53	15	15	31
3	Median	770	825	883	938	938	833	849	865	847	742	941	841
	Maximum	794	850	899	950	947	847	853	878	859	744	951	844
	Minimum	758	803	866	929	928	822	845	856	834	741	931	838
	Count	93	93	93	93	93	91	91	91	89	24	24	38
4	Median	802	869	919	969	968	864	870	895	872	742	970	850
	Maximum	818	883	929	978	975	871	875	904	880	742	976	851
	Minimum	780	851	909	953	957	852	856	885	857	741	963	844
	Count	29	29	29	29	29	27	27	27	27	8	8	15
5	Median	743	743	749	778	782	749	753	758	751	743	785	759
	Maximum	745	750	761	785	788	754	756	774	761	743	793	766
	Minimum	742	742	744	754	767	747	752	756	714	742	761	758
	Count	101	101	101	101	101	99	99	99	85	26	26	19

Table 5. Statistical summary of total dissolved gas saturations in the Columbia River from March 26 to March 30, 2012.

Event	Data	T1P2	T1P3	T1P4	T1P5	T1P6	T2P1	T2P2	T2P3	T3P1	CHJ	CHQW	WELLFB
1	Median	101.6	101.5	101.5	101.3	101.0	101.1	103.1	101.5	100.9	101.6	101.5	101.9
	Maximum	101.9	101.9	101.9	102.1	102.2	101.6	103.5	102.0	101.9	102.0	103.1	103.1
	Minimum	101.0	101.1	101.2	101.0	100.8	100.9	102.2	101.4	100.5	101.4	101.1	101.7
	Count	45	45	45	45	45	41	41	41	51	14	14	75
2	Median	107.5	115.8	122.5	125.4	124.3	114.8	117.1	118.7	116.8	101.5	124.3	114.7
	Maximum	110.6	118.5	123.9	126.1	125.4	116.3	117.8	119.7	117.6	101.6	125.0	115.1
	Minimum	104.4	112.0	118.8	122.5	123.9	113.3	116.7	117.7	112.9	101.4	123.7	111.7
	Count	57	57	57	57	57	55	55	55	53	15	15	31
3	Median	105.0	112.5	120.6	128.0	128.0	113.5	115.9	118.0	115.7	101.7	128.4	115.0
	Maximum	108.3	116.0	122.8	129.5	129.4	115.6	116.5	119.9	117.1	101.9	129.5	115.5
	Minimum	103.6	109.8	118.4	126.7	126.6	112.3	115.4	116.9	114.0	101.2	127.2	114.7
	Count	93	93	93	93	93	91	91	91	89	24	24	38
4	Median	109.2	118.3	125.1	132.0	131.8	117.8	118.5	122.1	119.0	101.5	132.1	116.9
	Maximum	111.4	120.3	126.5	133.2	132.7	118.6	119.3	123.1	120.3	101.6	132.8	117.2
	Minimum	106.1	115.8	123.7	129.7	130.2	115.9	116.5	120.4	116.7	101.3	131.0	116.2
	Count	29	29	29	29	29	27	27	27	27	8	8	15
5	Median	102.2	102.3	103.0	106.9	107.6	103.0	103.5	104.2	103.4	102.4	108.0	103.8
	Maximum	102.6	103.3	104.8	108.1	108.1	103.4	104.1	105.8	104.6	102.6	108.7	105.1
	Minimum	101.2	101.2	101.5	102.9	104.7	102.4	103.0	103.7	98.0	101.7	103.8	103.5
	Count	101	101	101	101	101	99	99	99	85	26	26	19

Figures

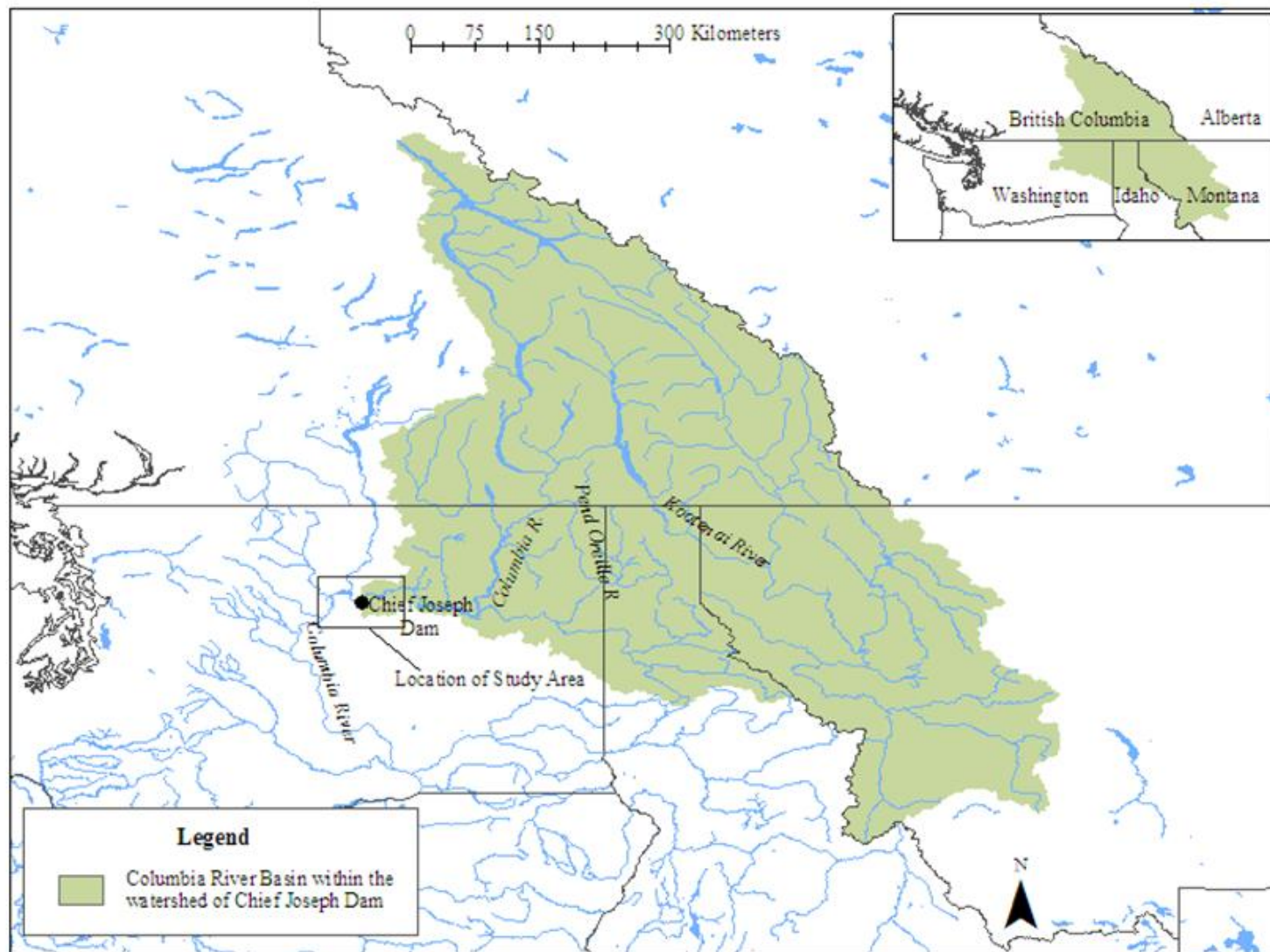


Figure 1. Location of the study area within the Columbia River watershed.

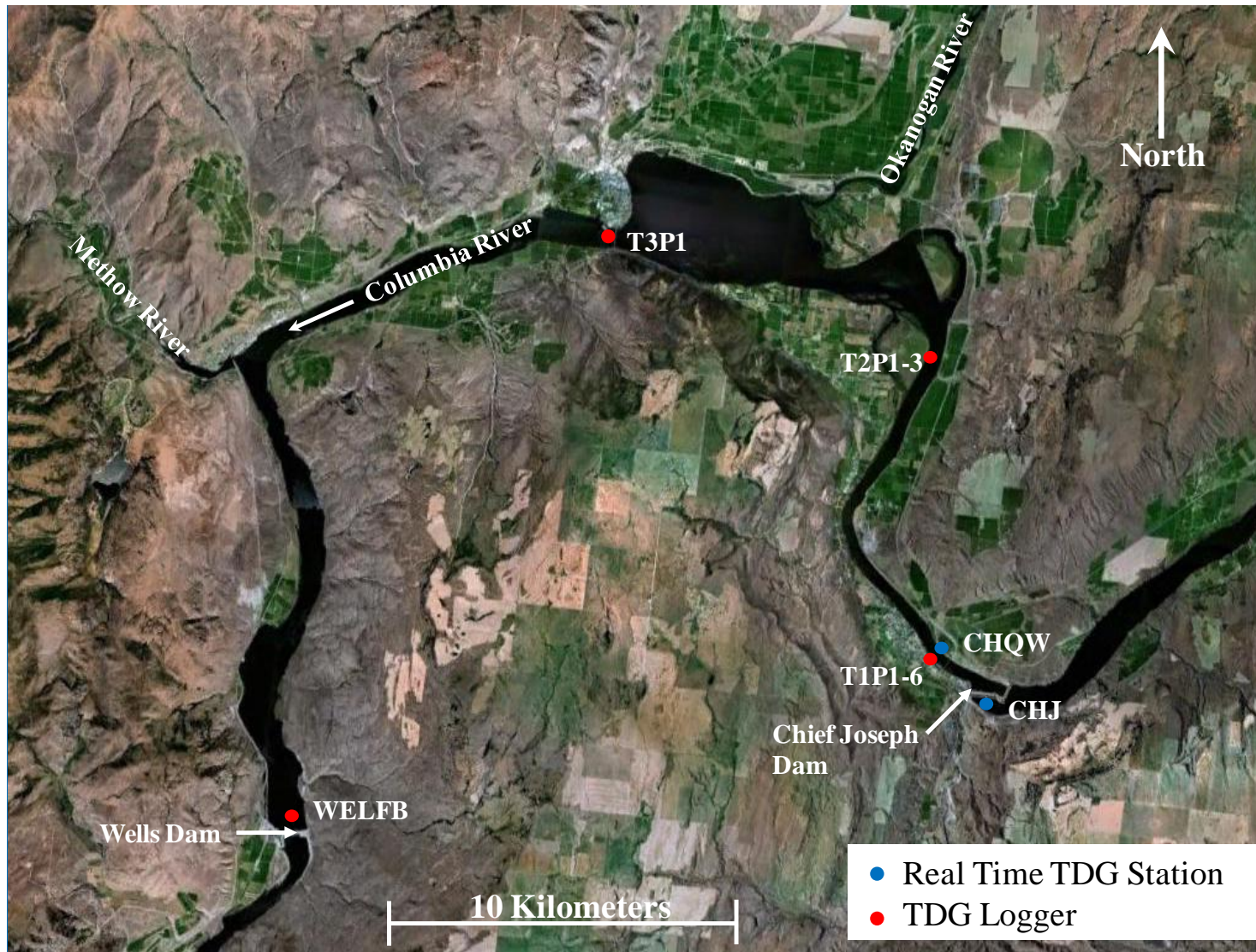


Figure 2. TDG and temperature monitoring stations downstream of Chief Joseph Dam to Wells Dam.



Figure 3. TDG and temperature monitoring stations upstream and downstream of Chief Joseph Dam.

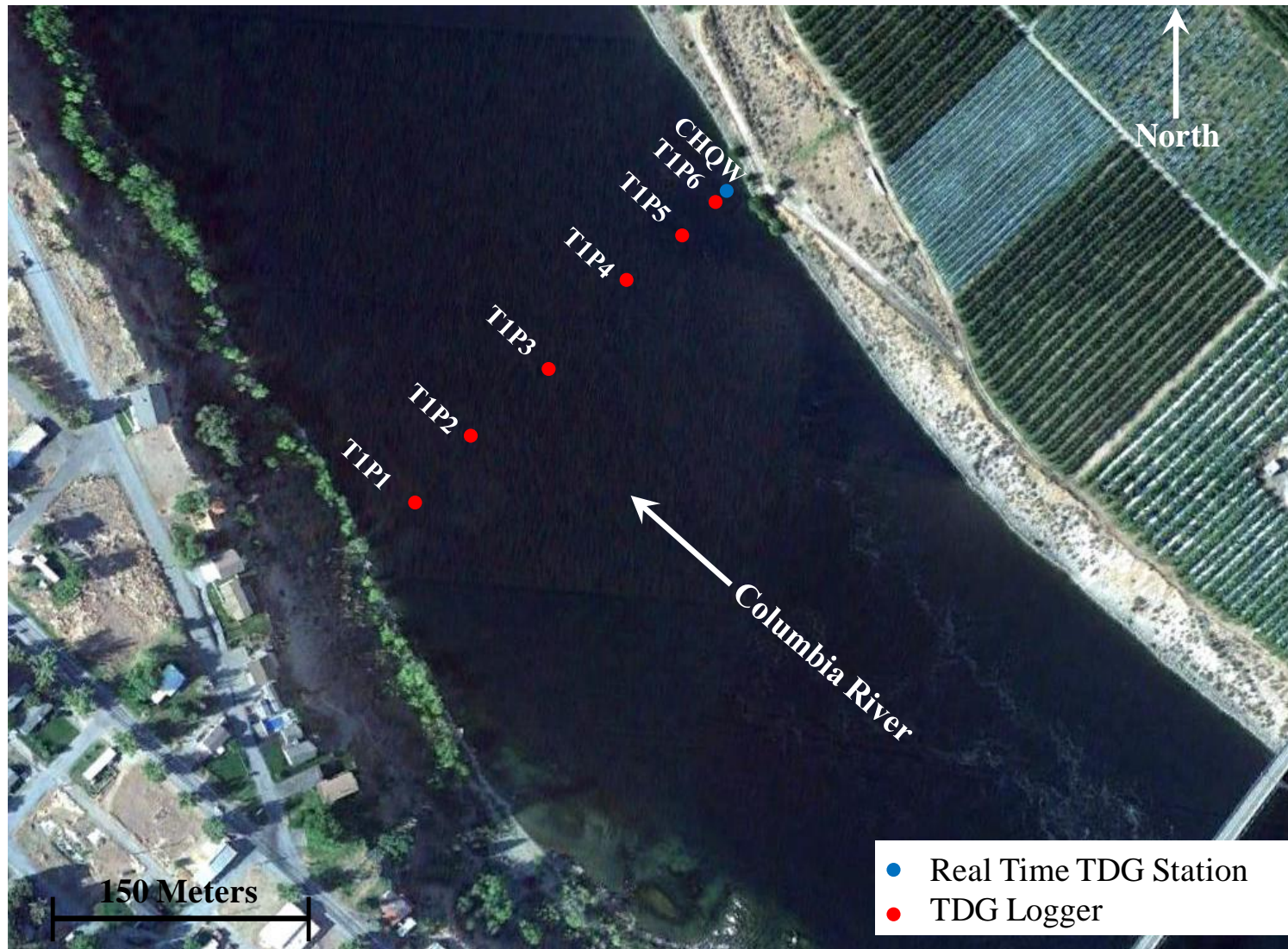


Figure 4. TDG and temperature monitoring stations at Transect 1 below Chief Joseph Dam.



Figure 5. TDG and temperature monitoring stations at Transect 2 below Chief Joseph Dam.

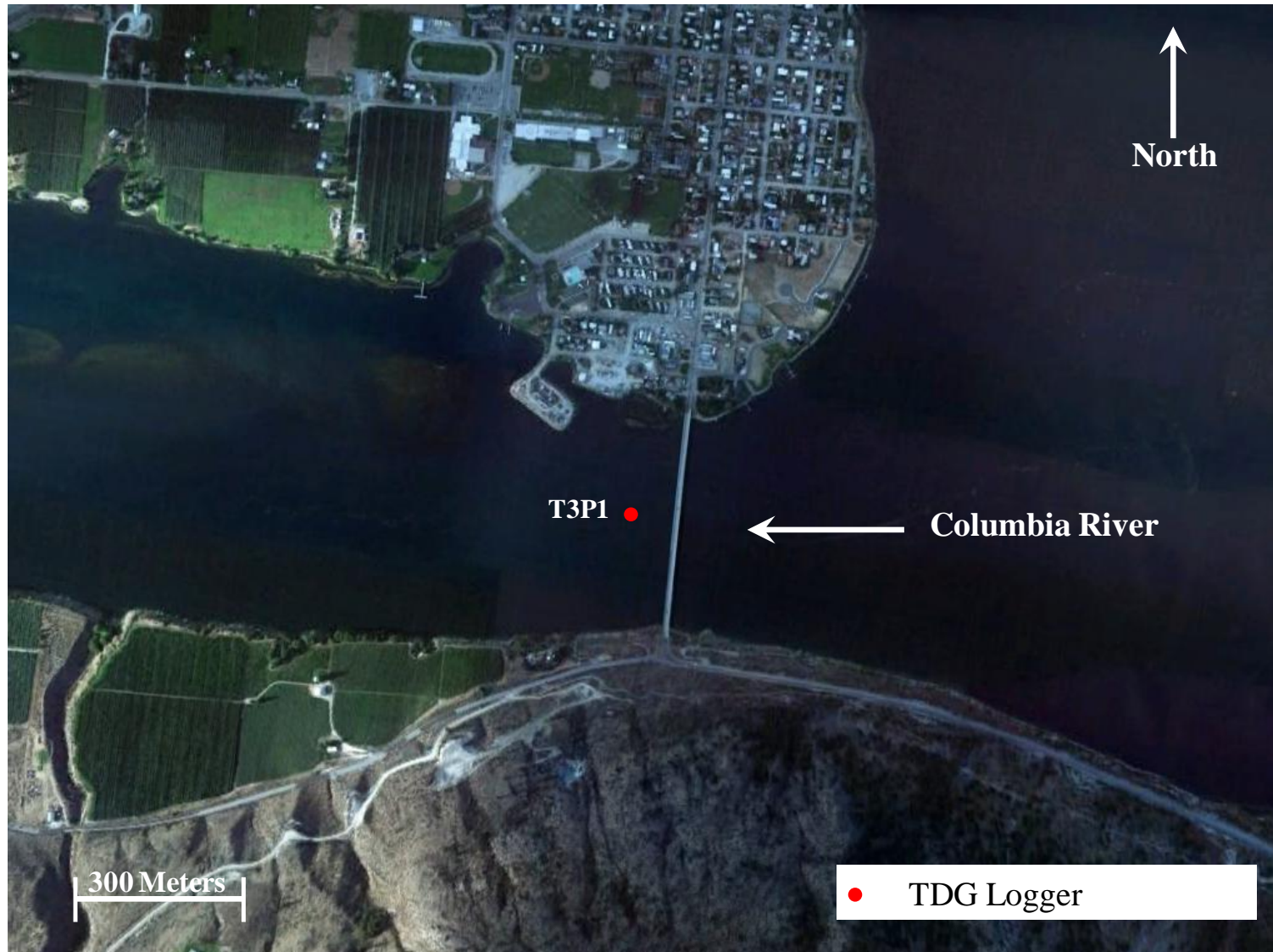


Figure 6. TDG and temperature monitoring stations at Transect 3 below Chief Joseph Dam.



Figure 7. Right bank spill trajectory (top photo) vs. left bank spill trajectory (bottom photo) during 30 kcfs/bay spillway release.

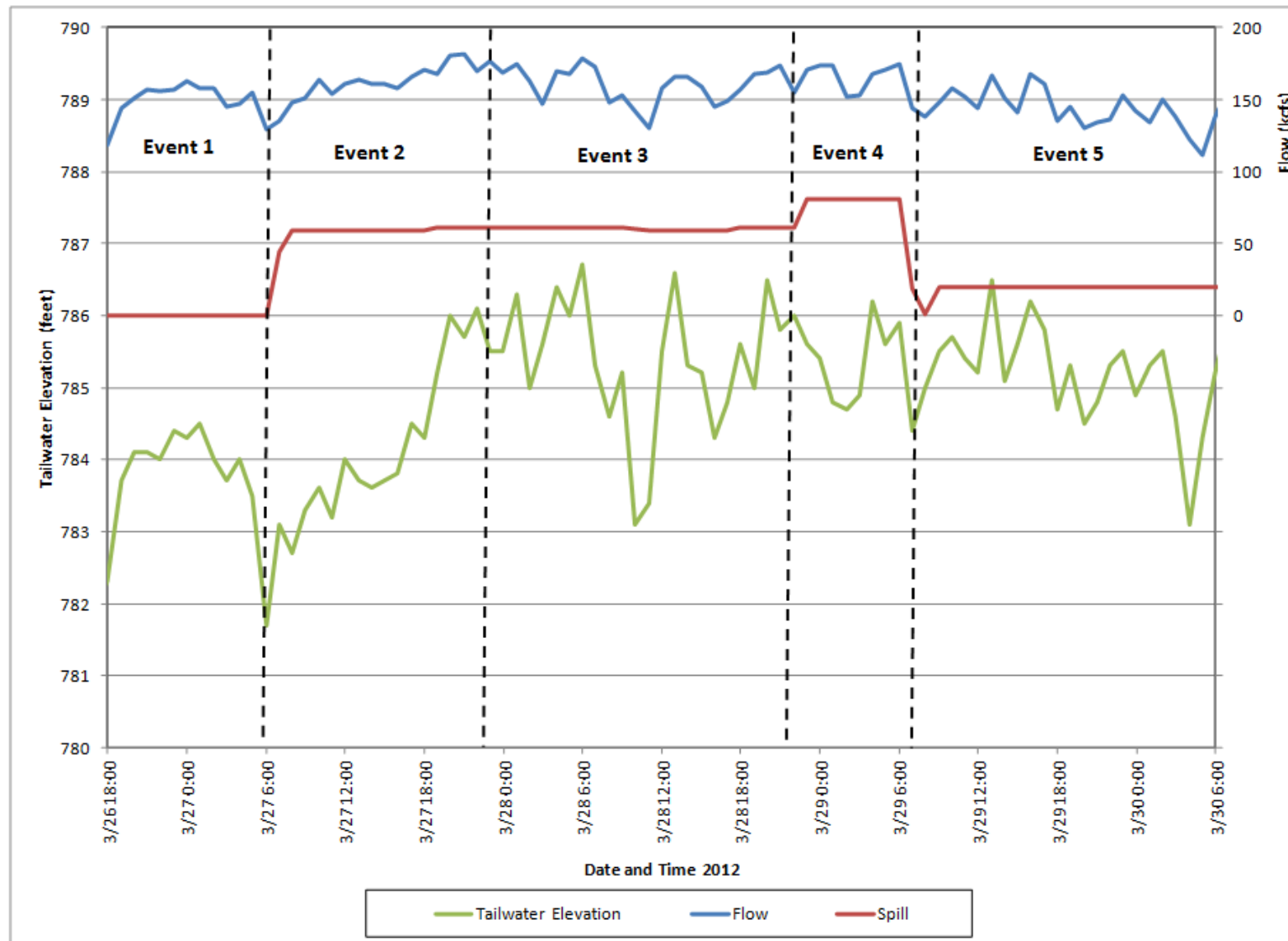


Figure 8. Chief Joseph Dam tailwater elevations during spillway operations.

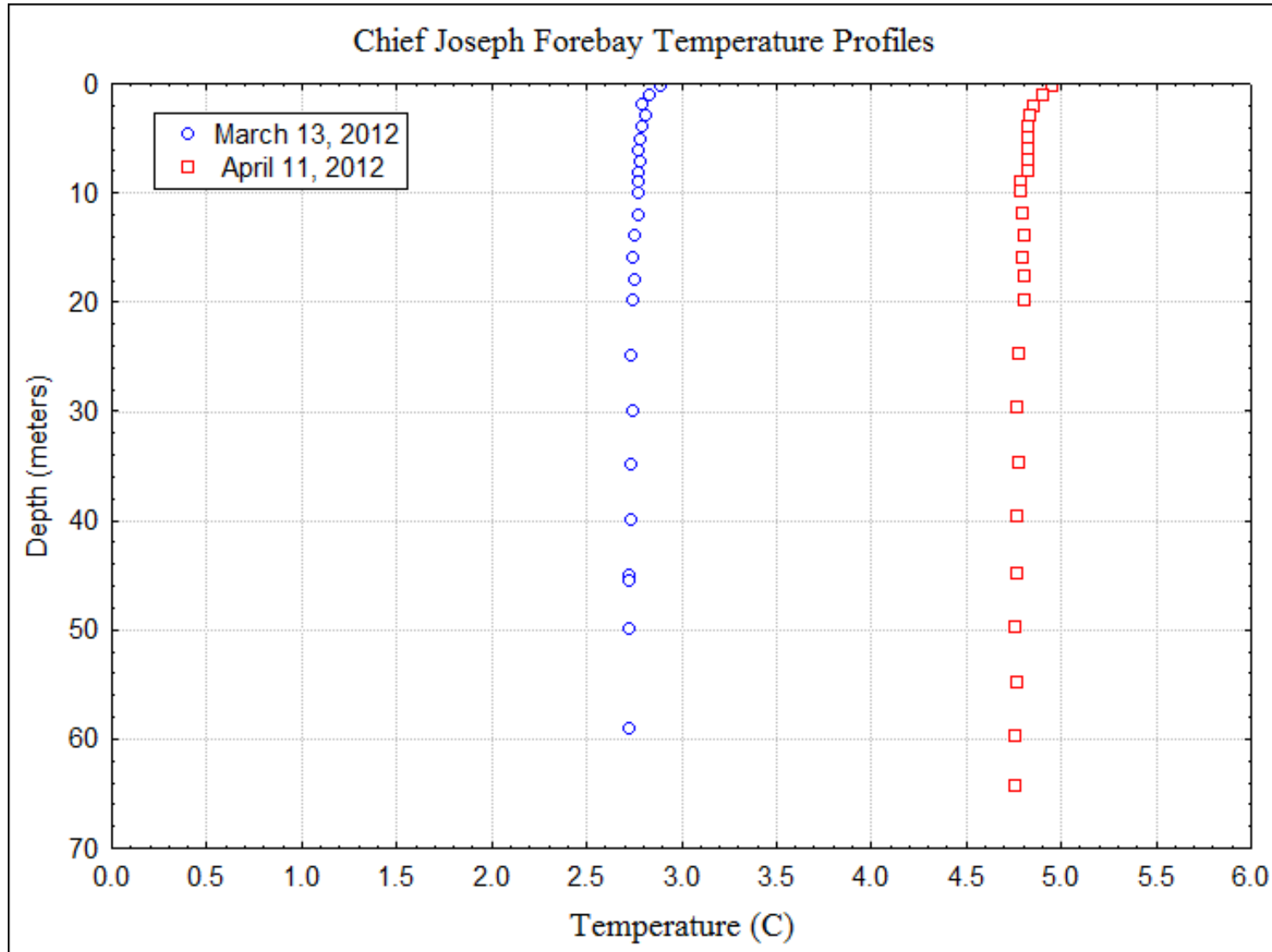


Figure 9. Chief Joseph Dam forebay temperature profiles in March and April 2012.

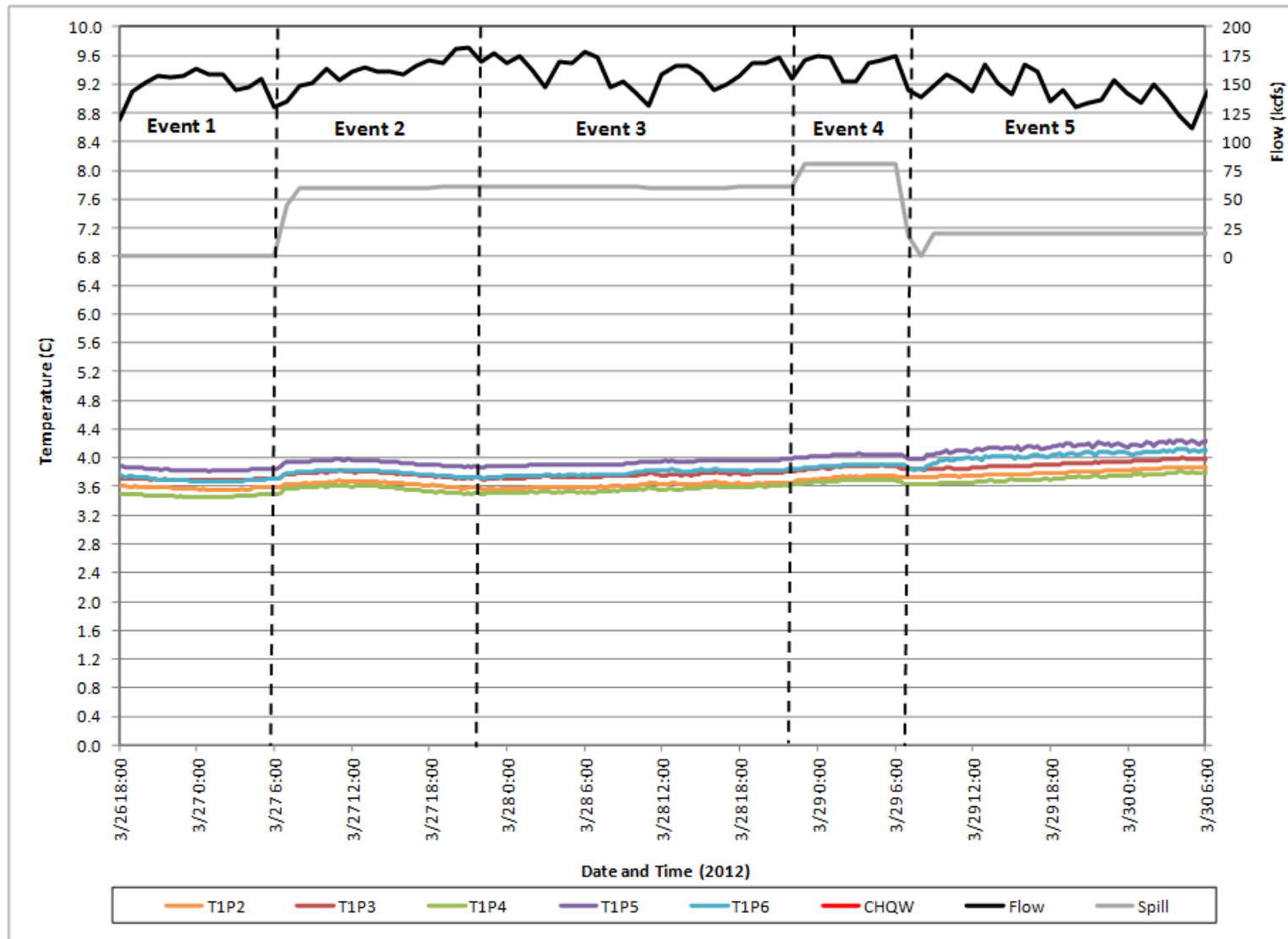


Figure 10. Time history of Columbia River temperatures at Transect 1.

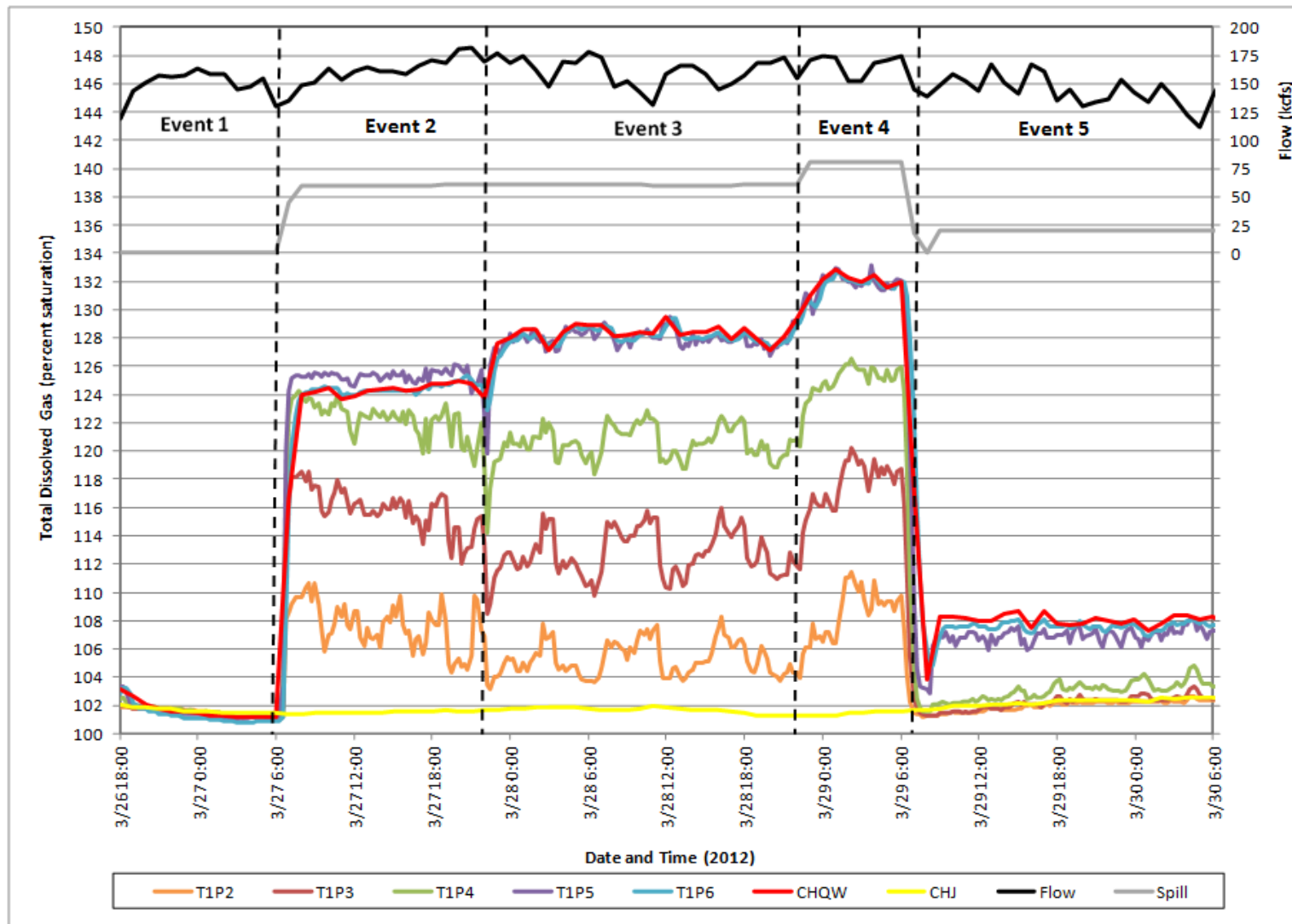


Figure 11. Time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1.

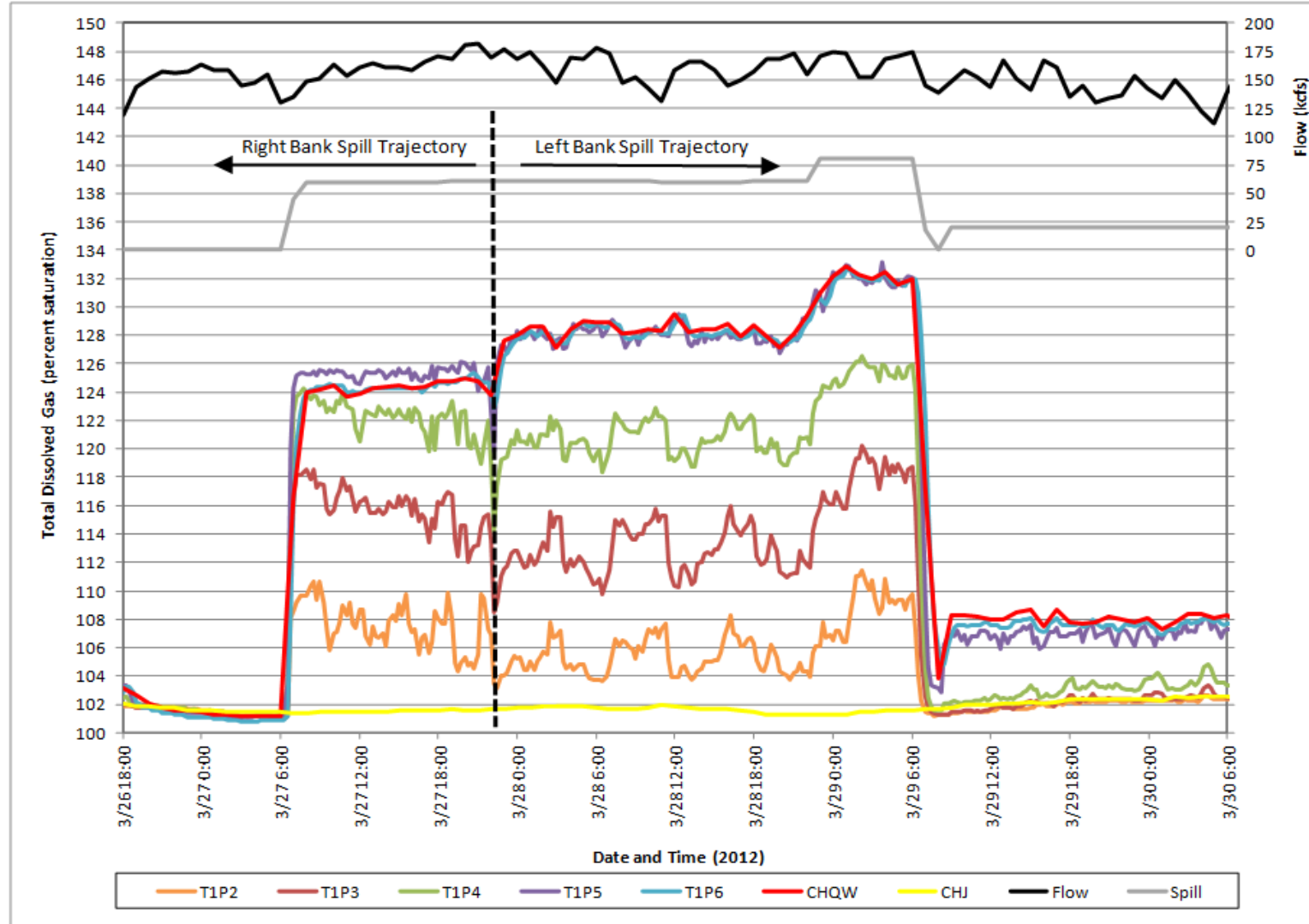


Figure 12. Time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1 showing left bank vs. right bank spill trajectory.

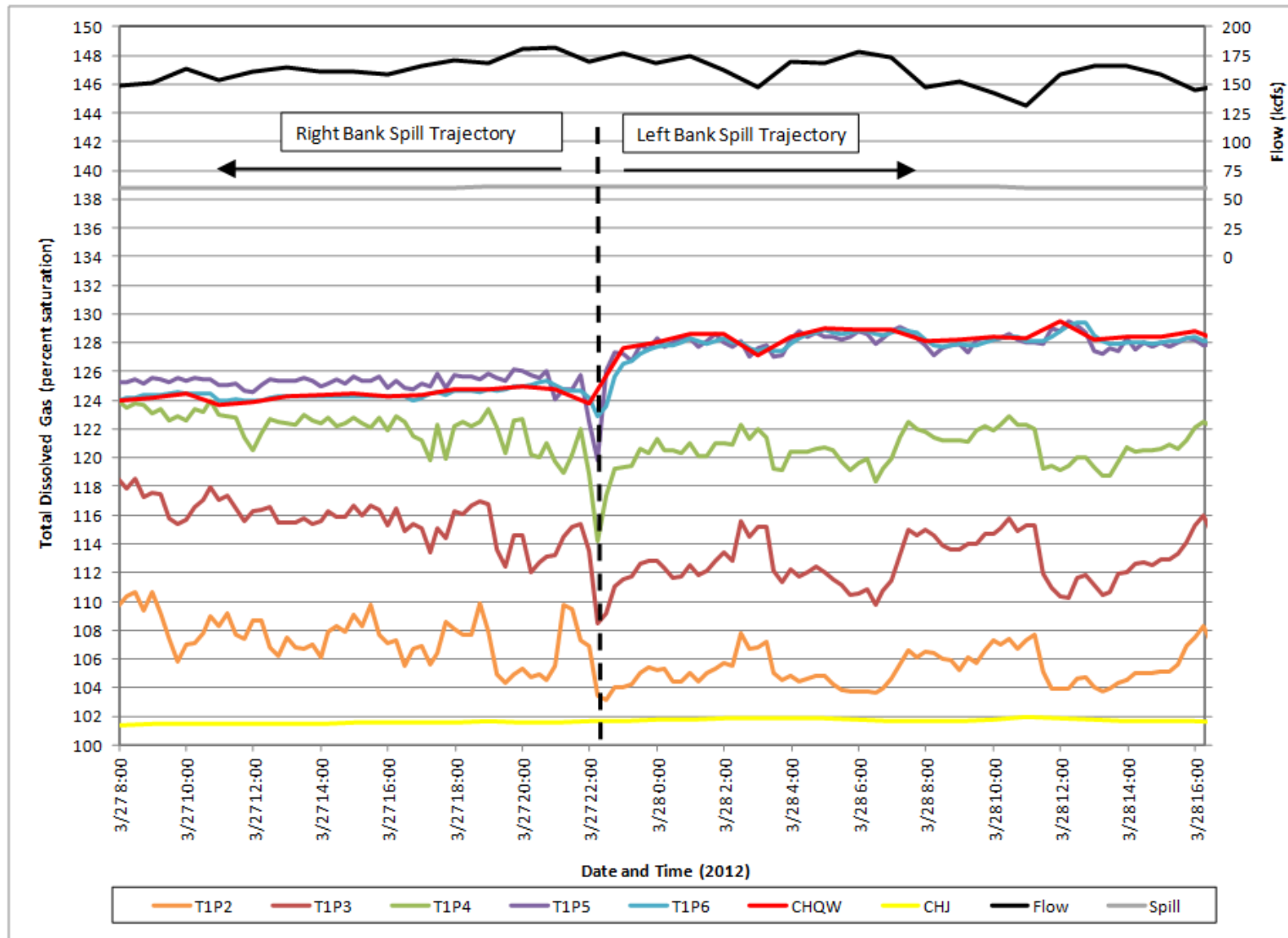
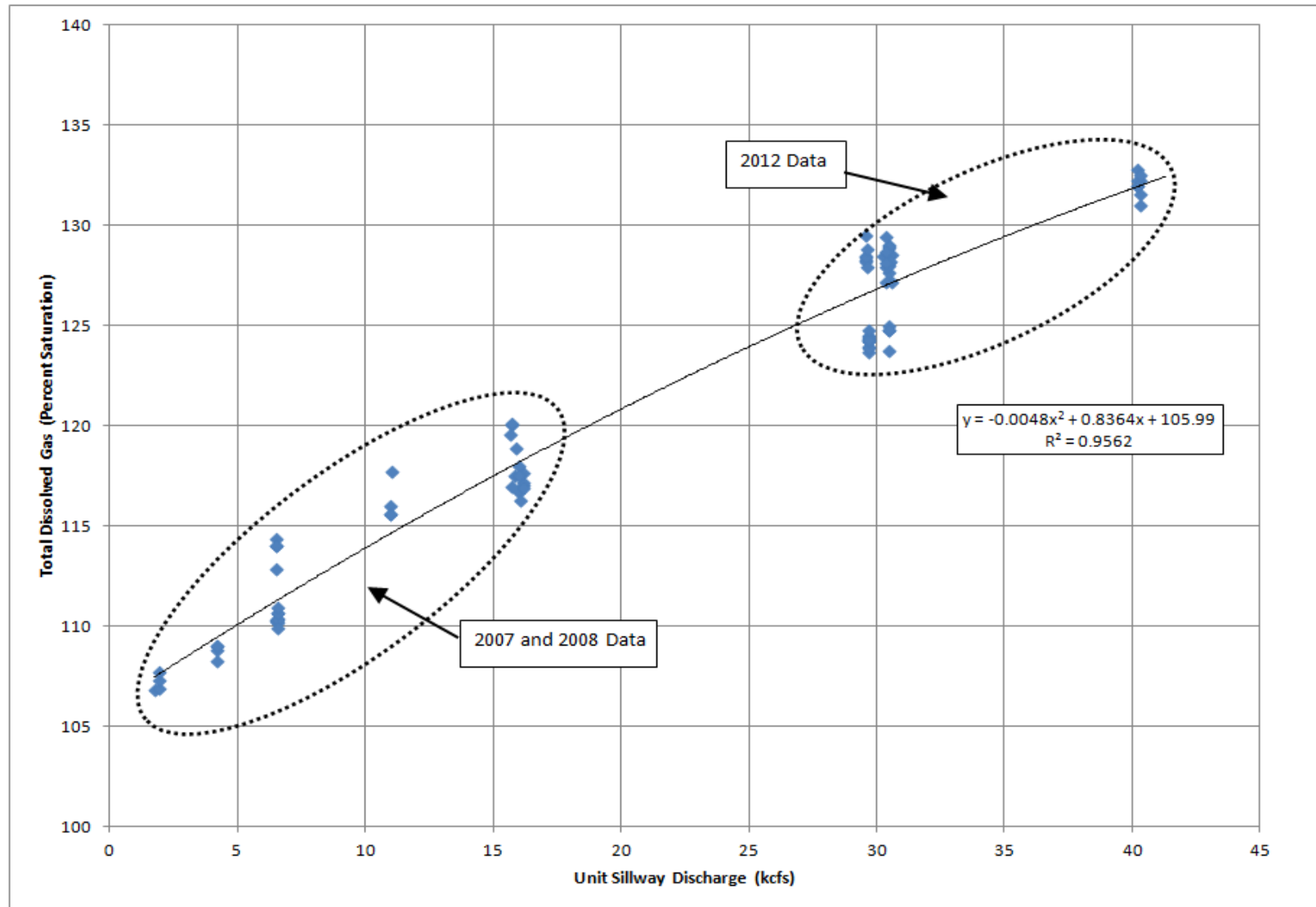


Figure 13. Expanded scale of time history of Columbia River TDG saturations immediately downstream of Chief Joseph Dam measured at Transect 1 showing left bank vs. right bank spill trajectory.



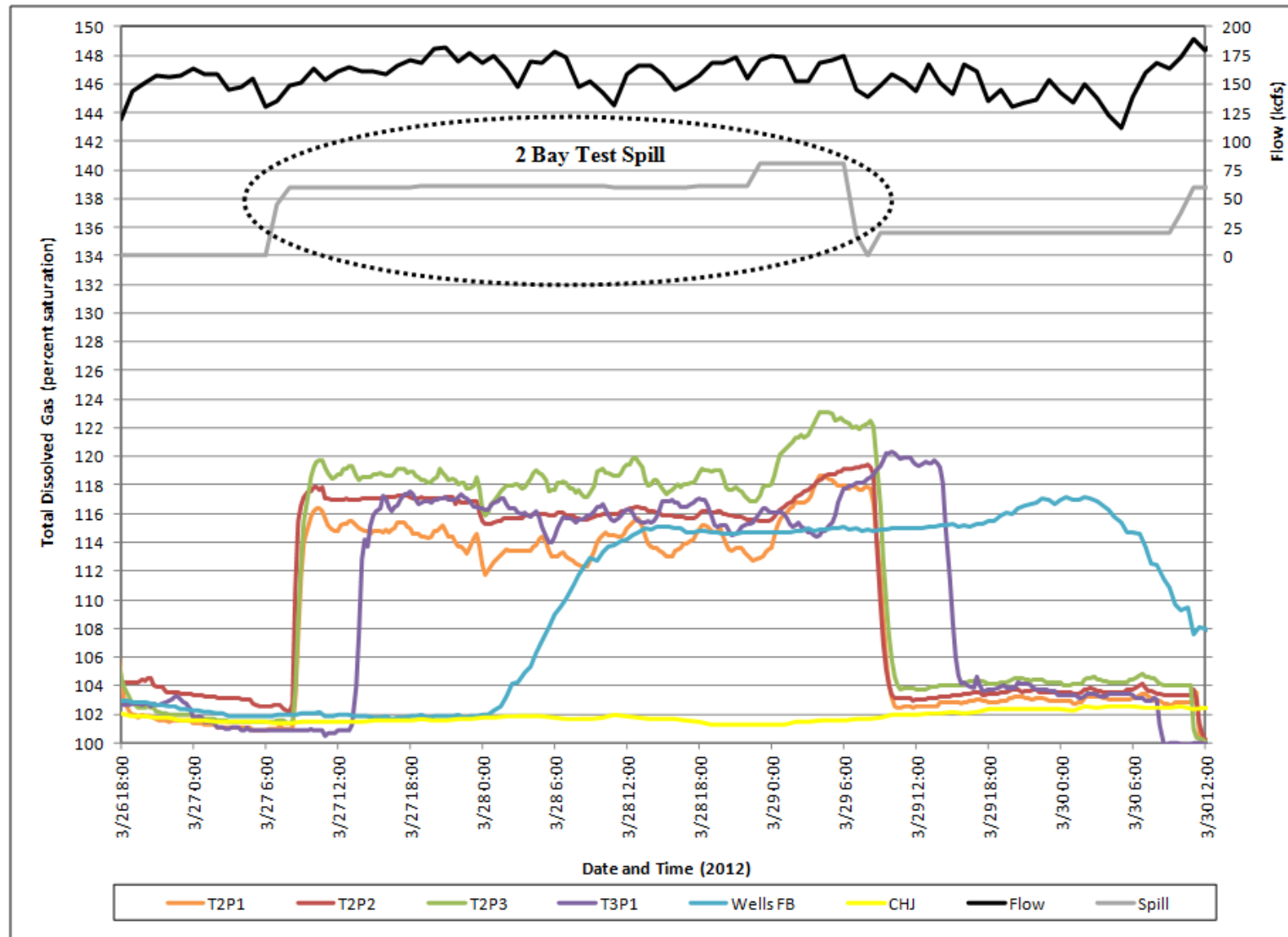


Figure 15. Time history of Columbia River TDG saturations as measured downstream of Chief Joseph Dam from Transect T2 to Wells Dam.